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Utilization of Fluctuations in Active Power Consumption of an Electric Arc Furnace for Optimizing the Slag Foaming Process

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Abstract

Production cost reduction is one of the main goals which have to be achieved by modern melt shops. Optimisation of various phases of the melting process carried out in a steelmaking electric arc furnace is one of the ways to achieve required targets. The present paper reveals the details of the stage of research consideration of power consumption fluctuations, or rather the level of its stabilization, in determining the optimal moment to introduce the foaming agent. In analysis, it was decided to use the 'moving coefficient of variation.
The aim of the conducted statistical analysis was to determine the width of the time interval for calculating the moving coefficient of variation of active power and the width of the time interval for its stable, predetermined value. Within this analysis, the non-parametric Friedman test was used, a post-hoc test in the variant proposed by Dunn was used, taking into account the so-called Bonferroni correction. Ultimately, the foamer dispenser control procedure was formulated.

Keywords: Electric arc furnace, Foaming slag, EAF active power, Power consumption fluctuations

1. Introduction

Nearly all large steel mills in Europe and Poland that use electric arc furnaces (EAF) for melting scrap operate using slag foaming technology. This technology allows for improved thermal efficiency of the electric arc and higher power output, thereby reducing the melting time. To fully utilize the advantages of slag foaming technology, it is necessary to ensure that the introduction of powdered carbon (foaming agent) into the bath allows for the electric arc to be as completely covered as possible for the longest time. An important issue is the assessment of the quality of slag foaming in the furnace and its impact on active power consumption and the stable operation of the electric arc.

The analyzed literature clearly indicates the possibility of finding a correlation between the noise emitted by an electric arc furnace (EAF) and the degree of slag foaming, where noise is one of several recorded parameters. The studies described in the literature focused on recording parameters such as energy consumption, oxygen activity in steel, the chemical composition of slag and steel, noise, furnace vibrations, current intensity and voltage measurements, and conducting FFT analyses. Measuring these parameters and conducting analyses should indicate whether the slag foaming process is proceeding correctly or not. The results of these measurements have allowed for the creation of algorithms or models, which in several steel mills have led to the automation and control of the slag foaming process, at least in the trial phase [1-3].

The aim of the research conducted by the authors is to optimize the slag foaming process in the electric arc furnace (EAF). This optimization involves finding the best moments to start and stop the introduction of the foaming agent into the EAF. The start and stop moments for introducing the foaming agent into the EAF should be determined in such a way that the slag foaming process leads to the maximum active power consumption allowed by the EAF transformer at that moment, without causing damage to the furnace's refractory lining. Introducing the foaming agent too early results in its suction into the dedusting system, wasting the agent and damaging the dedusting bags, while introducing it too late causes damage to the refractory lining by the electric arc and underutilization of the transformer's power.

Such optimization of the slag foaming process should primarily lead to a reduction in melting time, thereby increasing the efficiency of the Electric Arc Furnace (EAF), reducing the consumption of electrical energy, graphite electrodes, refractory materials, and the foaming agent itself, which in turn will also reduce CO_2 emissions into the atmosphere. In the studies conducted so far, the authors have shown that the appropriate moment to introduce the foaming agent is when the sound level drops to 103 dB [4]. However, during industrial trials, it was observed that the sound level reaches this reference value for only a few seconds. After reaching the reference value, the foaming agent was introduced, but the sound level increased, only to drop back to around 103 dB shortly after, and then it increased significantly until the end of the process, while power consumption fluctuations stabilized clearly. These observations led to the consideration of power consumption fluctuations, or rather the level of its stabilization, in determining the optimal moment to introduce the foaming agent.

2. Description of Smelting Technology

The tests were carried out during the operation of the EAF electric furnace (UHP type) with a capacity of 70 t, equipped with four oxygen-gas burners, of which three can also operate in the supersonic oxygen lance mode. The slag foaming material feeding lances are located under the oxygen-gas burners in the cold zones of the furnace. During melting, three baskets with scrap were charged into the furnace.

The measurements were made during heats of the same steel grade (S235JR). The scrap structure of the charge of each of the melts consisted of the following types of scrap: light scrap 42%, medium scrap 22%, heavy scrap 36%. The average power-on time (electric arc operating time) was 2400 seconds, the average electricity consumption was 337 kWh/t of liquid steel, the average foaming agent consumption was 6.43 kg/t of liquid steel.

3. Moving Coefficient of Variation

During the conducted research, it was observed that until clear stabilization, power consumption increases and simultaneously shows significant fluctuations. It was decided to evaluate the average course of power consumption increase using a moving average, while the magnitude of fluctuations (dispersion) was assessed using the standard deviation, also treating it as a moving quantity. With this approach, to compare the results obtained for different melts, it is advisable to use a relative measure of dispersion – the coefficient of variation:

$$\mathrm{VC} = 100 \cdot \underline{x}/\hat{s} \tag{1}$$

where: $\underline{x}$ - indicates the arithmetic mean calculated from an n-element sample,
$\hat{s}$ - indicates the standard deviation estimator calculated from an n-element sample.

In further analysis, it was decided to use the 'moving coefficient of variation.' The 'mobility' of the power consumption coefficient of variation results from the fact that the sample elements (active power values) are shifted by one second in subsequent calculation steps. The values of the coefficient of variation were calculated 'retrospectively.' This means they were assigned to the moment of the melt corresponding to the last second of the current n-second time interval. This approach is driven by the desire to develop an algorithm on which the online equipment controlling the introduction of the foaming agent into the furnace would operate.

The key problem, therefore, is to answer the questions: how wide should the time interval for calculating the power consumption coefficient of variation be, and what value of this coefficient will be most beneficial? Additionally, another question arises: is it sufficient to achieve this optimal value even for 1 second, or should a certain time interval be considered in which this value will meet specific conditions, e.g., it will not significantly increase, which is characteristic of unstable active power consumption? To answer these questions, a comprehensive statistical analysis was conducted, taking into account the following decision variables: values of the moving coefficient of variation: 3%, 4%, 5%, 6%, 8%, and 10%, width of the time interval for calculating the moving coefficient of variation: 5 s, 8 s, 10 s, 12 s, and 15 s, width of the time interval in which the coefficient of variation does not exceed the assumed value: 5 s, 10 s, and 15 s.

4. Research Results

The aim of the conducted statistical analysis was to determine the width of the time interval for calculating the moving coefficient of variation of active power and the width of the time interval for its stable, predetermined value. Within this analysis, the non-parametric Friedman test was used, prompted by a preliminary analysis of the normality of distributions, the time after which the foaming agent should be introduced. In the vast majority of cases, the verification of the normality of these distributions, conducted using the Shapiro-Wilk test [5], was negative. The Friedman test is used to verify the hypothesis of no differences between measurement series of the same feature determined under several (more than two) conditions.

In the case of statistically significant differences, a so-called post-hoc test is conducted, which provides detailed information about which series differ significantly and which do not. In the analysis discussed, a post-hoc test in the variant proposed by Dunn was used, taking into account the so-called Bonferroni correction

[6]. The results of the Friedman test, presented in Figures 1 to 3 and in Tables 1 to 3, are practically unambiguous. In the vast majority of cases, the series of designated moments of foamer application differ significantly due to the width of the time interval for calculating the moving coefficient of variation of active power for each of the accepted threshold values of this coefficient.

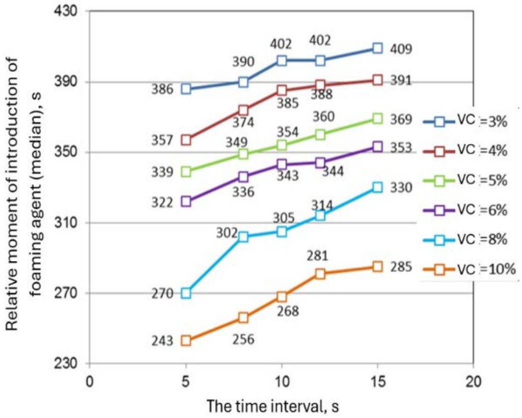

Fig. 1. Results of the Friedman test and Dunn-Bonferroni post-hoc tests (stabilization time of the coefficient of variation minimum 5 s)

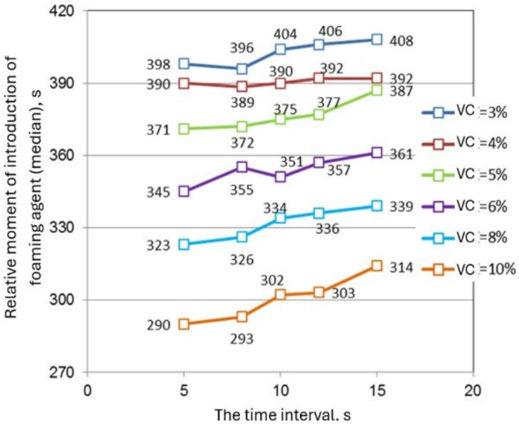

Fig. 2. Results of the Friedman test and Dunn-Bonferroni post-hoc tests (stabilization time of the coefficient of variation minimum 10 s)

Table 1.
Results of the tests in assessing the significance of differences in relative moments of foamer application depending on the width of the time interval for determining the coefficient VC (stabilization time of the coefficient of variation minimum 5 s)

Dunn-Bonferroni post-hoc test Comparison	VC=3%	VC=4%	VC=5%	VC=6%	VC=8%	VC=10%
	Results of the Friedman test					
	Fr=150,7 p<0,001	Fr=171,4 p<0,001	Fr=179,0 p<0,001	Fr=153,2 p<0,001	Fr=164,9 p<0,001	Fr=171,5 p<0,001
5 s – 8 s	0,009	0,286	0,007	0,001	0,007	0,038
5 s – 10 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
5 s – 12 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
5 s – 15 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
8 s – 10 s	0,006	0,038	0,146	0,284	0,012	0,002
8 s – 12 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
8 s – 15 s	<0,001	<0,001	<0,001	0,041	<0,001	<0,001
10 s – 12 s	0,224	0,007	0,002	<0,001	0,264	0,147
10 s – 15 s	<0,001	<0,001	<0,001	0,006	<0,001	<0,001
12 s – 15 s	0,047	0,001	0,014	0,001	0,002	0,005

Table 2.
Results of the tests in assessing the significance of differences in relative moments of foamer application depending on the width of the time interval for determining the coefficient VC (stabilization time of the coefficient of variation minimum 10 s)

Dunn-Bonferroni post-hoc test Comparison	VC=3%	VC =4%	VC =5%	VC =6%	VC =8%	VC =10%
	Results of the Friedman test					
	Fr=92,3 p<0,001	Fr=129,9 p<0,001	Fr=107,2 p<0,001	Fr=114,2 p<0,001	Fr=92,3 p<0,001	Fr=119,7 p<0,001
5 s – 8 s	0,252	1,000	1,000	0,014	0,663	0,837
5 s – 10 s	<0,001	0,006	0,007	<0,001	0,003	<0,001
5 s – 12 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
5 s – 15 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
8 s – 10 s	0,038	0,024	0,115	1,000	0,246	0,009
8 s – 12 s	<0,001	<0,001	<0,001	0,001	<0,001	<0,001
8 s – 15 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
10 s – 12 s	0,169	0,001	0,024	0,031	0,083	0,459
10 s – 15 s	0,002	<0,001	0,032	<0,001	<0,001	<0,001
12 s – 15 s	0,757	0,386	1,000	0,012	0,064	0,004

Table 3.
Results of the tests in assessing the significance of differences in relative moments of foamer application depending on the width of the time interval for determining the coefficient VC (stabilization time of the coefficient of variation minimum 15 s)

Dunn-Bonferroni post-hoc test Comparison	VC=3%	VC=4%	VC=5%	VC=6%	VC=8%	VC=10%
	Results of the Friedman test					
	Fr=42,5 p<0,001	Fr=94,6 p<0,001	Fr=79,0 p<0,001	Fr=67,0 p<0,001	Fr=55,7 p<0,001	Fr=75,3 p<0,001
5 s – 8 s	1,000	1,000	1,000	0,455	0,327	1,000
5 s – 10 s	0,551	0,551	0,001	0,124	0,004	0,010
5 s – 12 s	0,003	<0,001	<0,001	<0,001	<0,001	<0,001
5 s – 15 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
8 s – 10 s	0,060	0,210	0,058	1,000	0,622	0,029
8 s – 12 s	<0,001	<0,001	<0,001	0,026	0,006	<0,001
8 s – 15 s	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
10 s – 12 s	0,338	0,035	0,534	0,124	0,455	0,125
10 s – 15 s	0,017	<0,001	0,001	<0,001	0,006	0,001
12 s – 15 s	1,000	0,003	0,163	0,018	0,622	0,622

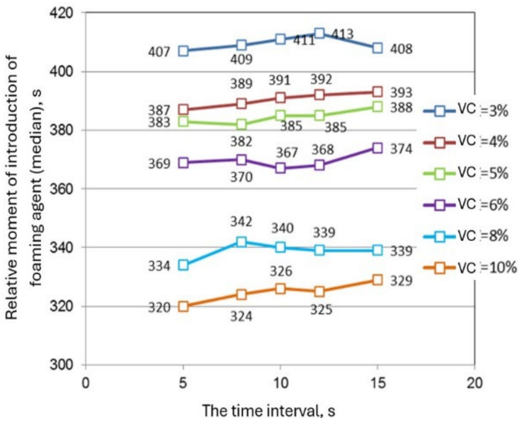

Fig. 3. Results of the Friedman test and Dunn-Bonferroni post-hoc tests (stabilization time of the coefficient of variation minimum 15 s)

A detailed analysis of the significance of differences using the post-hoc test indicates that not all series differ significantly. While in the case of a stabilization time of 5 s (Fig. 1, Tab. 1), the lack of statistically significant differences is incidental (orange background of the table cells under the figure), in the other two cases (stabilization time of 10 s – Fig. 2, Tab. 2 and 15 s – Fig. 3, Tab. 3), there are many differences that do not show statistical significance. It is worth noting that the lack of differences most often concerns the series of foamer application moments for 8 s and 10 s, as well as 10 s and 12 s.

5. Summary and conclusions

When discussing the obtained results, it should be stated that the result of the Friedman test indicates (in general terms) statistically significant differences in the moments of foamer application depending on the adopted value of the coefficient of variation. Detailed conclusions are provided by the results of the post-hoc test. In both cases, there are no statistically significant differences between the moments of foamer application for adjacent values of the coefficient of variation. The only exception to this rule is the difference between the series for the coefficients of variation of 6% and 8%, which shows characteristics of statistical significance. This effect is most likely caused by the first sequential two-percent jump in the threshold value of the coefficient of variation.

Considering the discussed results, a decision should be made regarding the 'optimal' value of the coefficient of variation, which could constitute the final outcome of the statistical analysis. A coefficient of variation value of 3% is probably too restrictive and causes excessive shifting of the foamer application moment. The choice, therefore, comes down to selecting one of the values 4%, 5%, and 6%. The middle value seems to have the most advantages, which is largely supported by the results of the post-hoc tests presented in Figures 2 and 3. For the five-percent coefficient of variation, the most arguments were observed in favor of selecting a ten-second interval for calculating its value. Ultimately, the following foamer dispenser control procedure can be formulated: interval width for calculating the moving coefficient of variation 10 s, interval width for stabilizing its value 10 s, and threshold value of the coefficient of variation 5%.

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